Design, construction, alignment, and calibration of a compact velocimetry experiment

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ABSTRACT

A velocimetry experiment has been designed to measure shock properties for small cylindrical metal targets (8-mm-diameter by 2-mm thick). A target is accelerated by high explosives, caught, and retrieved for later inspection. The target is expected to move at a velocity of 0.1 to 3 km/sec. The complete experiment canister is approximately 105 mm in diameter and 380 mm long. Optical velocimetry diagnostics include the Velocity Interferometer System for Any Reflector (VISAR) and Photon Doppler Velocimetry (PDV). The packaging of the velocity diagnostics is not allowed to interfere with the catchment or an X-ray imaging diagnostic. A single optical relay, using commercial lenses, collects Doppler-shifted light for both VISAR and PDV. The use of fiber optics allows measurement of point velocities on the target surface during accelerations occurring over 15 mm of travel. The VISAR operates at 532 nm and has separate illumination fibers requiring alignment. The PDV diagnostic operates at 1550 nm, but is aligned and focused at 670 nm. The VISAR and PDV diagnostics are complementary measurements and they image spots in close proximity on the target surface. Because the optical relay uses commercial glass, the axial positions of the optical fibers for PDV and VISAR are offset to compensate for chromatic aberrations. The optomechanical design requires careful attention to fiber management, mechanical assembly and disassembly, positioning of the foam catchment, and X-ray diagnostic field-of-view. Calibration and alignment data are archived at each stage of the assembly sequence.

Keywords: velocimetry, VISAR, PDV, optical calibration, optical alignment, photon budget, fiber optics, opto-mechanics, shock physics

1. PURPOSE AND DESCRIPTION OF EXPERIMENT

This velocimetry experiment was designed to generate data that validate shock physics material models. The experiment involved shocking a metal target with a disc of explosive material. A coherent picture of the shock event resulted from three types of measurements: metallurgy, radiography, and velocimetry. The target was caught in foam, retrieved, and later subjected to a metallurgical examination. The evolution of the damage was recorded by a dense plasma focus machine, Cygnus, which executes a time-resolved X-ray radiographic diagnostic.[1] Cygnus recorded the target's initial location, the condition of the damaged target before it entered the foam, and the target's final position. The initial conditions, evolution of the target shock breakout surface, shock pressure, and damage after detonation were captured by optical velocimetry measurements. The velocimetry measurements recorded the component of velocity that was perpendicular to the target surface at four defined spatial locations. The velocity measurements were accomplished with Photon Doppler Velocimetry (PDV)[2,3] and Velocity Interferometer System for Any Reflector (VISAR)[4,5,6] diagnostics. Twelve experiments were executed with excellent results.

The design of the experimental instrument, called the canister, has three important components. First is the foam, calibra-

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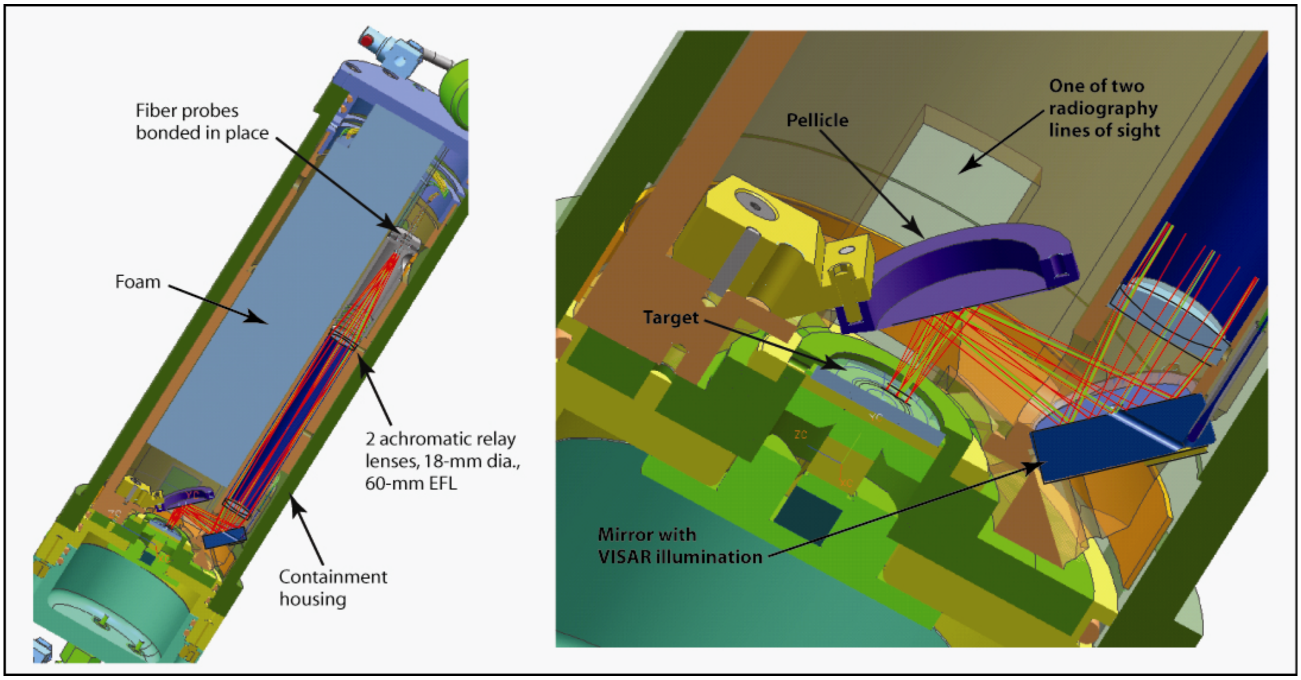


Fig. 1. Cutaway views of the experiment canister.

Fig. 2. The target is retrieved from the foam after the experiment.

ted to catch the target without adding further damage. Next are two nearly unobstructed lines of sight that enable recording of the initial X-ray images. Finally, the optics and their supporting structures perform velocimetry measurements. The diagnostics need to be compatible with the detonation apparatus and all the surrounding issues such as triggering and containment.

Figure 1 shows two cutaway views of the canister. The outermost shell, the containment housing, surrounds the optics cell, which is pinned in place. The optics cell contains fiber probes for VISAR and PDV, relay optics, a turning mirror, a pellicle, and the catchment foam. The fiber probes are potted in steel tubes that are inserted into the optics cell, located with a small setscrew (during the alignment procedure), and then glued in place. Illumination for the VISAR probes is provided by a fiber-coupled collimating lens that is bonded to the turning mirror. The optics cell is easily removable; this simplifies post-experiment foam inspection (Figure 2). The electronic instrumentation (discussed in Section 2) and interferometers are located about 100 m from the canister. The optical and optomechanical designs are discussed in Section 4.

2. SYSTEM-LEVEL OVERVIEW

The electronic instrumentation system is divided into the following subsystems: timing and firing (T&F), process control (PC), cross timing (CT), and the various users. The T&F subsystem controls the master trigger pulses that set off the experiment. The PC subsystem monitors operational parameters to verify that the electronics are performing correctly. The CT subsystem monitors the signal delays between the diagnostics so that the individual triggers fire in the correct sequence. The users include scientists obtaining PDV, VISAR, and Cygnus data (in this paper, they are identified by their diagnostic abbreviation, i.e., “PDV”), and those detonating high explosives (HE). These relationships are summarized in Figure 3. An example of one of the users, PDV, is summarized in

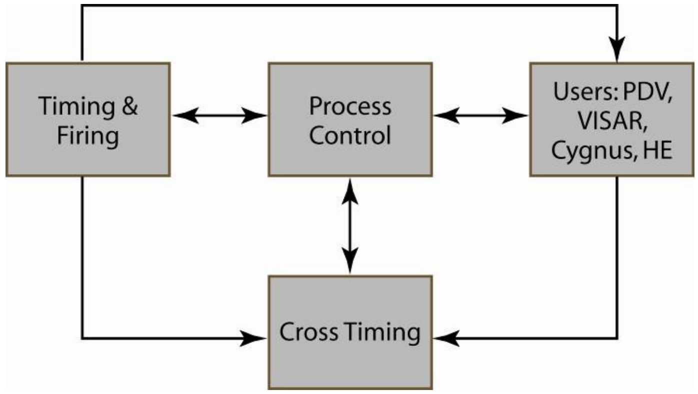


Fig. 3. System-level block diagram.

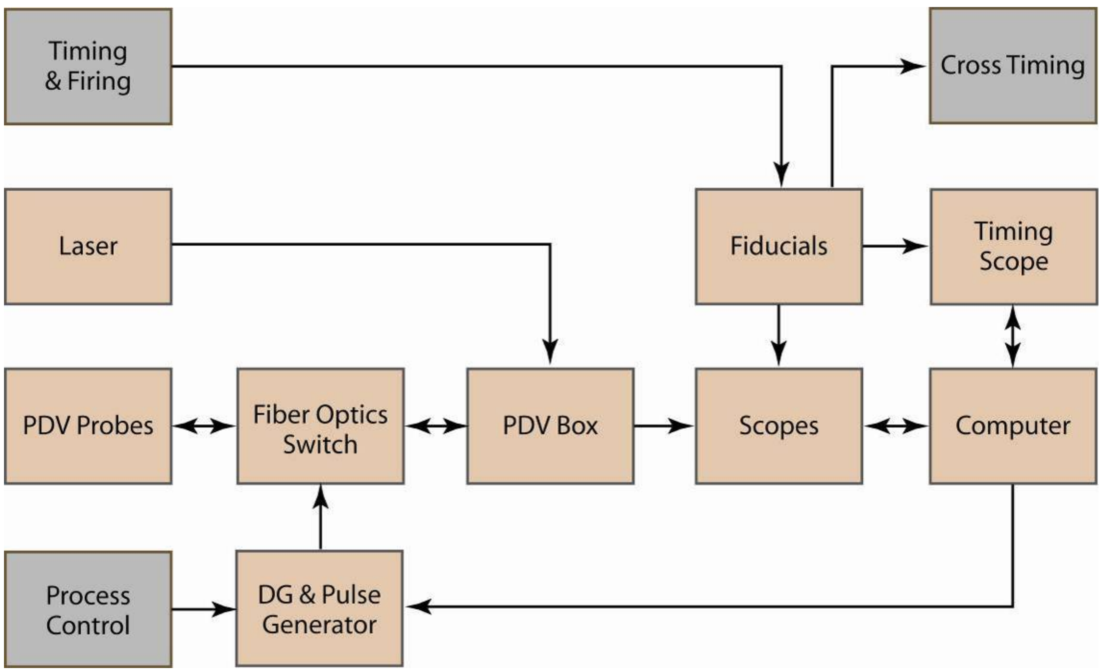


Fig. 4. Block diagram of a diagnostic for a PDV user.

Figure 4. The PDV diagnostic system receives inputs from T&F, a laser, the actual PDV probes in the instrument canister, and PC. The PDV interferometers and detectors are contained in the PDV box. Light from the probes to the PDV box and from the laser are controlled by fiber-optic switches. Signals from the PDV box are routed through two oscilloscopes to a computer. Two oscilloscopes are used to increase the dynamic range of the measurement.

3. VELOCIMETRY DESIGN

In general, the shock waves being measured will have velocity components that are both perpendicular and parallel to the surface being measured. The parallel components are not directly measured by the present velocimetry diagnostics. The phenomenon of shock waves reaching the measurement surface is known as shock breakout. The time from detonation to shock breakout is about 1 to 2 μsec.

The primary goal of velocimetry is to capture the initial details of the shock breakout. Unfortunately, these measurements are the most difficult to achieve. A secondary goal is to capture the evolution of surface velocities in the first 15 mm of travel, as the target begins to spall.

Any description of the design requirements is somewhat arbitrary, since the requirements represent a compromise between what is specified and what is possible with current technology. Table 1 contains design requirements for a typical system.

Table 1. Functional requirements for velocimetry.

Characteristics	Specification	Comments
Expected velocity range	0.1 to 3 km/sec	
Temporal resolution	1 nsec	
Absolute velocity accuracy	0.1%	
Spatial resolution	100–200 μm	Derived from temporal resolution and velocities
Field of view (FOV)	4 mm	
Measurement points	4 discrete locations	One on-axis, three equally spaced on the edge of the FOV
Tracking distance	15 mm	Need maximum resolution at start
Data requirements		Agreement between diagnostics and simulations

The design requirements for velocimetry were best met by a combination of both PDV and VISAR. An additional benefit of this approach is that the data may be checked for consistency. Each experimental instrument has four PDV probes, one in the center of the FOV and three equally spaced on a 4-mm-diameter circle. Four point measurements allow extraction of the target tilt in addition to the center velocity. The canister has two VISAR probes that are nearly collocated with two of the PDV probes, one in the center and one at the FOV's edge.

In these experiments, both VISAR and PDV took point measurements of the surface using fiber-optic probes. This constraint allowed remote measurement, reduced cost, and was easily integrated into the containment housing. The end of the fiber or probe tip was potted into a stainless steel tube (Figure 5). The potted probes were bonded into the housing after the best focus was measured for each probe.

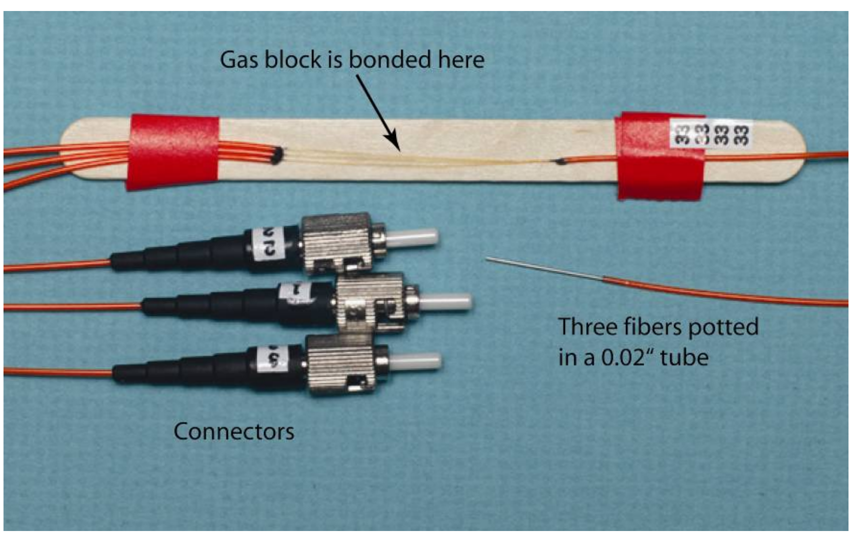


Fig. 5. Final configuration of the three-fiber VISAR probe.

Table 2. Requirements and qualitative differences between VISAR and PDV.

REQUIREMENTS		
Characteristics	**VISAR**	**PDV**
Temporal resolution	1 nsec	10 nsec
Absolute velocity accuracy	Error is a function of signal amplitude and other factors	0.1%[7]
Spatial resolution	≥ 100 µm	≥ 10 µm
Tracking distance (for required velocities)	0–3 mm	15 mm
Dynamic range	8 bits	5–7 bits at 1–2 GHz
Signal requirements	10:1 signal-to-noise in time domain	10:1 db signal-to-noise in frequency domain
Bandwidth requirements	2 GHz	8–10 GHz
QUALITATIVE DIFFERENCES BETWEEN METHODS		
Measurements	Velocity	Displacement
Fiber type	Multimode (100-µm core)	Single mode (10-µm core)
Wavelength	532 nm	1550 nm
Probe tip coating	Not needed	Antireflective (AR) coating
Failure modes	Many optical elements that are sensitive to misalignment	Acoustical vibrations of fibers introduces noise into the data

The interferometers and data recording were located and performed remotely. The VISAR interferometer uses bulk optics that require alignment and adjustment, whereas the PDV interferometer is an all-fiber system that only requires a contrast adjustment. In VISAR, vibrations, changes in temperature, or moving air currents can ruin fringe contrast by introducing spurious optical path differences. VISAR requires a continuous data record; a break in the data record results in an unknown offset to the velocity estimate. Although PDV is not very sensitive to mechanical disturbances, acoustic modes in fibers can introduce noise. PDV fibers must be located away from fans or other sources of mechanical vibrations. Additionally, PDV is susceptible to back-reflections, backscatter, and self-resonance, which is typically corrected by applying an antireflection (AR) coating on all optical surfaces, including the forward ends of the fibers (probe tips). The differences between these two systems are summarized in Table 2.

3.1 PDV

The PDV interferometer combines Doppler-shifted light with a reference (unshifted) beam (Figure 6). The beat frequency of the combined light is proportional to the target velocity at the point of measurement. Multiple velocities may be resolved by means of a fast Fourier transform of a data window. The ability to resolve multiple frequencies is useful because it allows the measurement of multiple velocities as the surface spalls and produces ejecta.

The quoted (see Table 2) value of 0.1% absolute velocity accuracy was measured by Jensen[7] for the case of a constant velocity target. Since the target velocity is changing for the experiment, the instantaneous velocity will be different from the measured velocity due to the temporal resolution of the instrument. Two other factors (in addition to temporal resolution) influence the velocity accuracy: 1) laser wavelength is specified to ±0.01 nm at 1550 nm; and 2) the time base of the scope (specified by the manufacturer to be a few parts per million).

The tracking distance is the length over which useful data is returned after detonation. The ability of PDV to track over long distances is important to investigators. In many of these experiments, the PDV diagnostic was able to track for 15 mm. The target punctures the pellicle after 15 mm of travel (Figure 1).

One interesting feature of PDV is that a single fiber is used for both transmission and reception. It is important to control illumination backscattering from the optics since this reduces fringe contrast. One important source of backscatter is the

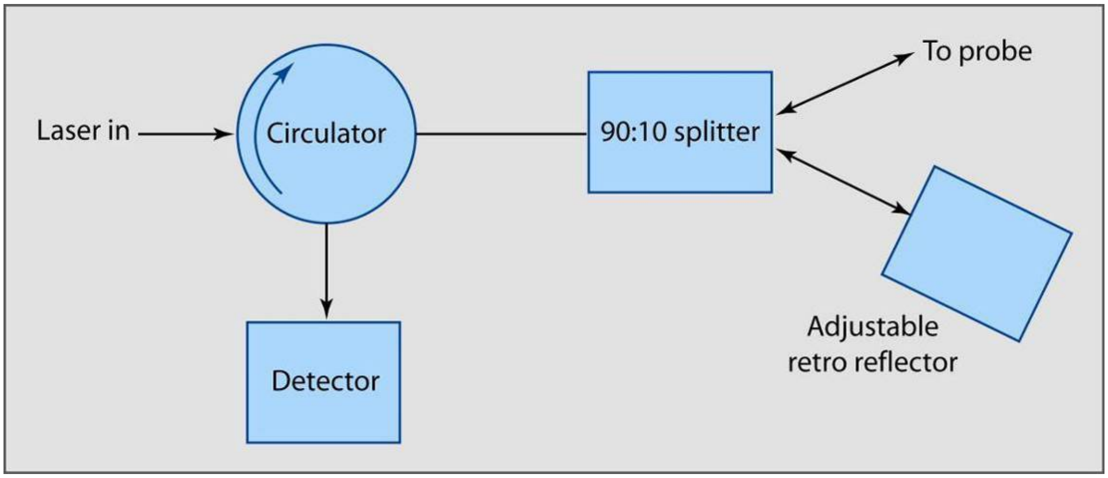


Fig. 6. PDV diagnostic block diagram. The PDV combines Doppler-shifted light with a reference (unshifted) beam.

fiber probe surface. Initially, the fiber-optics were ordered with prepolished ends and AR coating. However, inserting the fibers into stainless steel tubes caused some damage to the fiber ends. Polishing and applying AR coating, after potting the fibers into the tubes, minimized the risk of damage.

We designed the PDV probes to use single-mode 10/125 fiber at a wavelength of 1550 nm. These parameters were chosen because of the availability of high-quality telecommunications equipment, such as circulators and detectors that use single-mode fiber at 1550 nm.[8]

3.2 VISAR

Inside the VISAR interferometer, an interference pattern is set up between returning light and returning light that is time-delayed by passing through an etalon. VISAR diagnostics measures the velocity of a moving surface by recording the Doppler wavelength shift of the returning light (Figure 7).

VISAR was chosen to measure jump-off speed to within several nanoseconds of shock breakout. In order to resolve details of the shock event, it was important that the design meet the requirement of 1-nsec temporal resolution. However,

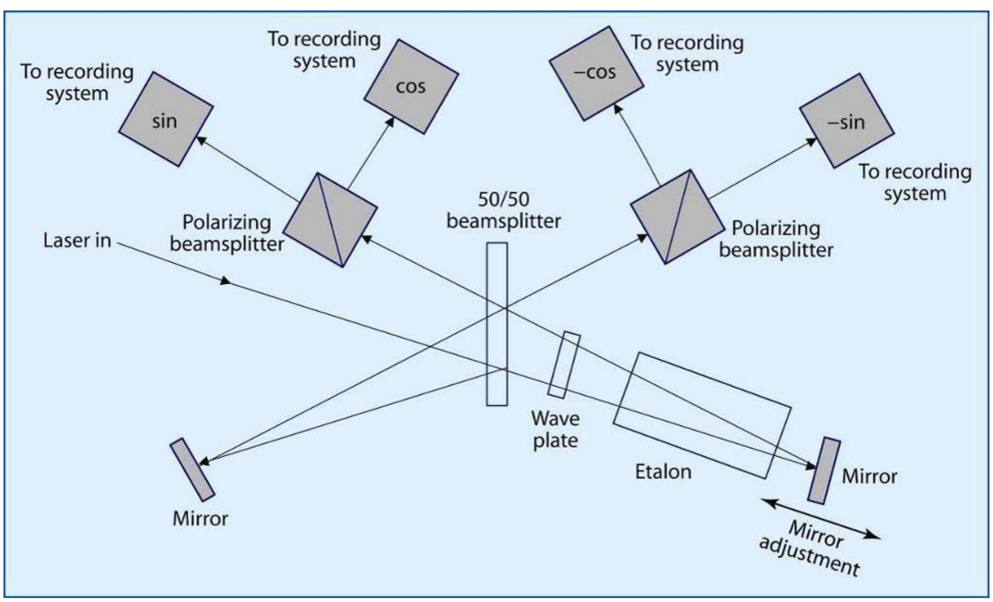


Fig. 7. VISAR diagnostic block diagram.

VISAR suffers a loss of signal while the shock wave sweeps across the measurement spot and, unlike PDV, VISAR has difficulty resolving multiple velocities.

The light from each VISAR probe passes through two interferometers. One interferometer is shown in Figure 7. The two interferometers have etalons with different fringe constants (and lengths) to resolve phase ambiguities in the velocity record.

Each VISAR interferometer records in quadrature, allowing the experimenter to reduce uncertainty regarding phase, and to distinguish between a dark fringe and loss of signal. The recording systems may be either a streak camera with a charge-coupled-device readout or detectors with digitizers. Each recording option has its advantages and limitations. A streak camera system has a 16-bit dynamic range and is more sensitive, but is more limited in the record length than is a digitizer. The streak cameras have 100-psec resolution. Digitizers have an 8-bit dynamic range and a much longer data record for a given amount of memory than a streak camera system.[9]

VISAR, in contrast to PDV, requires a separate multimode illumination (send) fiber. The light is injected into the system after the last lens to suppress scattered light. Each illumination fiber has an attached collimating lens to control the illumination spot size. The mismatch between the illumination spot size (1.3 mm nominal) and the receive fiber diameter (100-μm core) is a significant factor in the VISAR photon budget (described further in Section 4).

Each VISAR receiving probe originally had one multimode fiber potted in a small steel tube. Later, three fibers were potted in each probe to increase light throughput and mitigate the risk of data loss due to breakage. Throughput was increased by dedicating two of the three fibers to the two interferometers. The third spare fiber was potted in each probe; this spare could be used to potentially replace either of the two working fibers if they became damaged during assembly or transport. For example, the fibers may be damaged when bonded to the gas block. The gas block is an aluminum tube bonded to the bare fibers for containment purposes.

4. OPTICS AND OPTOMECHANICS

The optical system is a partially achromatized f/4 relay with 1:1 magnification (Figures 1 and 8). No aperture stop was used, but the lenses were set up to send and receive light, normal to both the target surface and the optical fibers (telecentric condition). Telecentricity on the target side minimizes vignetting due to shock-induced curving and warping of the target. The commercial lenses used in the optical system required special AR coating for both 532 and 1550 nm. The pellicle is the only optical element in the projectile's path, so that the projectile would experience minimal disturbance when entering the foam.

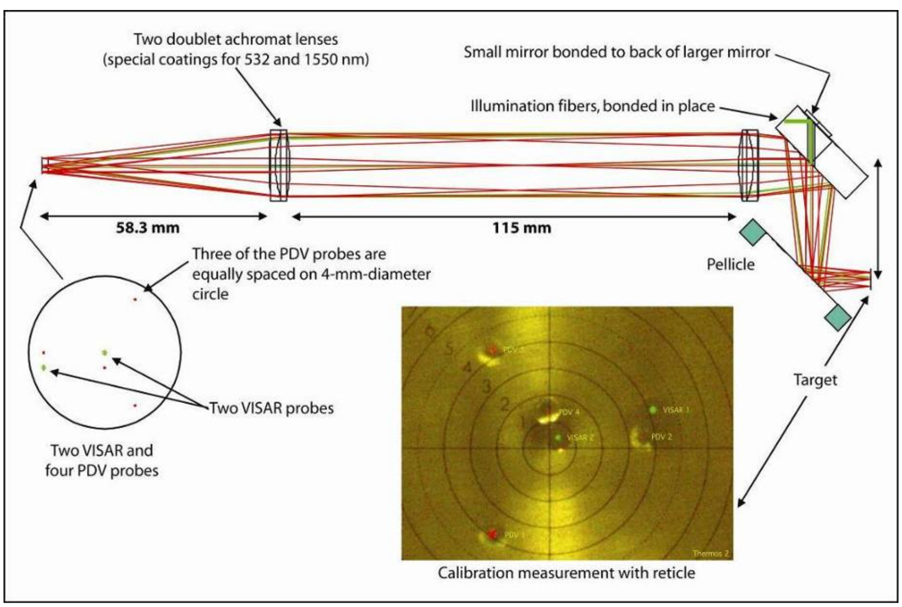


Fig. 8. Optical layout and probe layout. The two image planes on the left result from a slight focus shift between PDV and VISAR.

Fig. 9. Fused silica turning mirror with holes.

The illumination design for VISAR required collimated light to be injected into the glass turning mirror (Figure 9). We potted a fiber-coupled collimating lens into a 1.5-mm-diameter steel tube and then potted the tubes into small holes in the mirror. Size constraints made it inadvisable to bend the fiber. Instead, the illumination was turned by a small (9-mm-square, 1-mm-thick) mirror mounted to the back of the primary mirror. The small holes (Figure 9) were fabricated at a 45° angle by using a proprietary ultrasonic drilling technique.[10] Chipping of the mirror surface can be reduced by using a special ophthalmic tape.[11] The surface flatness of the uncoated glass was λ/10 before drilling and λ/9 after drilling.[12]

The laser, the interferometer, and the recording apparatus were located about 100 m from the canister. As shown in Table 3, the VISAR input laser emits close to 10 W, and line items 1 through 3 captured light losses prior to light entering the canister. Line item 2 includes the effect of a Pockels cell. The cell gates the light entering the canister so that the pellicle was not damaged by the approximately 2 W impinging on its surface. Approximately 9 μW were collected on the detector surface (Table 3, line item 12).

With the PDV system, the signal into the oscilloscope is proportional to

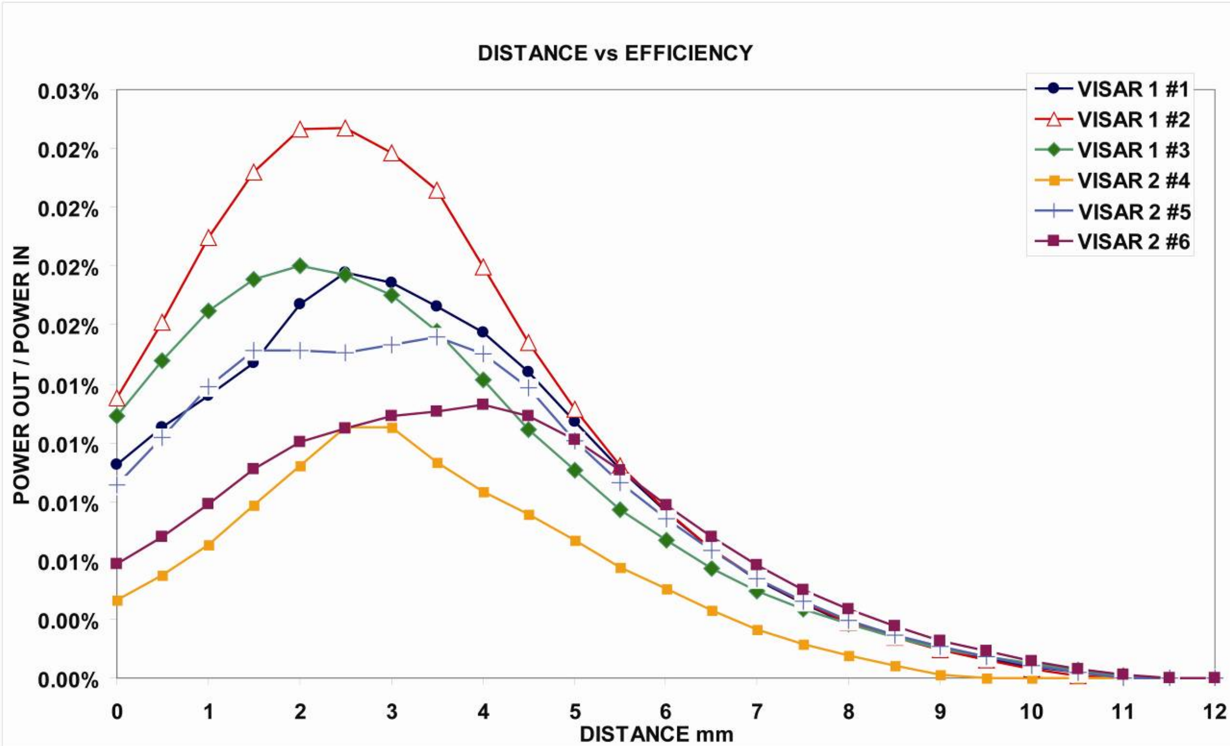
$$V_D \sqrt{I_S I_U} \tag{1}$$

where V_D is the instrument constant; I_S is the power of shifted light, and I_U is the power of unshifted light.

Consequently, modest attenuation of the shifted light due to system losses may be compensated with a proportional increase to the unshifted light; hence the experimenters are not as concerned with the PDV photon budget as they are with VISAR. A commonly used ratio of unshifted to shifted light is 100:1; an extensive discussion of this subject is given by Rutkowski.[13] The system has an adjustment that allows modification of this ratio (Figure 6).

Table 3. VISAR photon budget.

#	Description	% Passing	Power Remaining (W)	Comments
1	Input laser	100%	1.0000E+01	10-W laser
2	Coupling to fiber	30%	3.0000E+00	
3	Loss in fiber	79%	2.3700E+00	100 m of 50-μm core, 10 db/km loss
4	Illumination efficiency	85%	2.0145E+00	Light loss between illumination fiber and target
5	Probe efficiency	1.69%	3.4045E–02	Equals NA^2, NA = 0.13
6	Surface reflecting efficiency	50%	1.7023E–02	
7	Loss due to spot size mismatch	1%	1.7023E–04	
8	Optical efficiency	95%	1.6171E–04	Effect of lenses, mirrors, coatings
9	Coupling back into fiber	95%	1.5363E–04	
10	50/50 split and ST connector	39%	5.9915E–05	
11	Return fiber	58%	3.4751E–05	100 m of graded density fiber, 23.5 db/km
12	VISAR	25%	8.6877E–06	Loss inside interferometer; result: ~9 μW



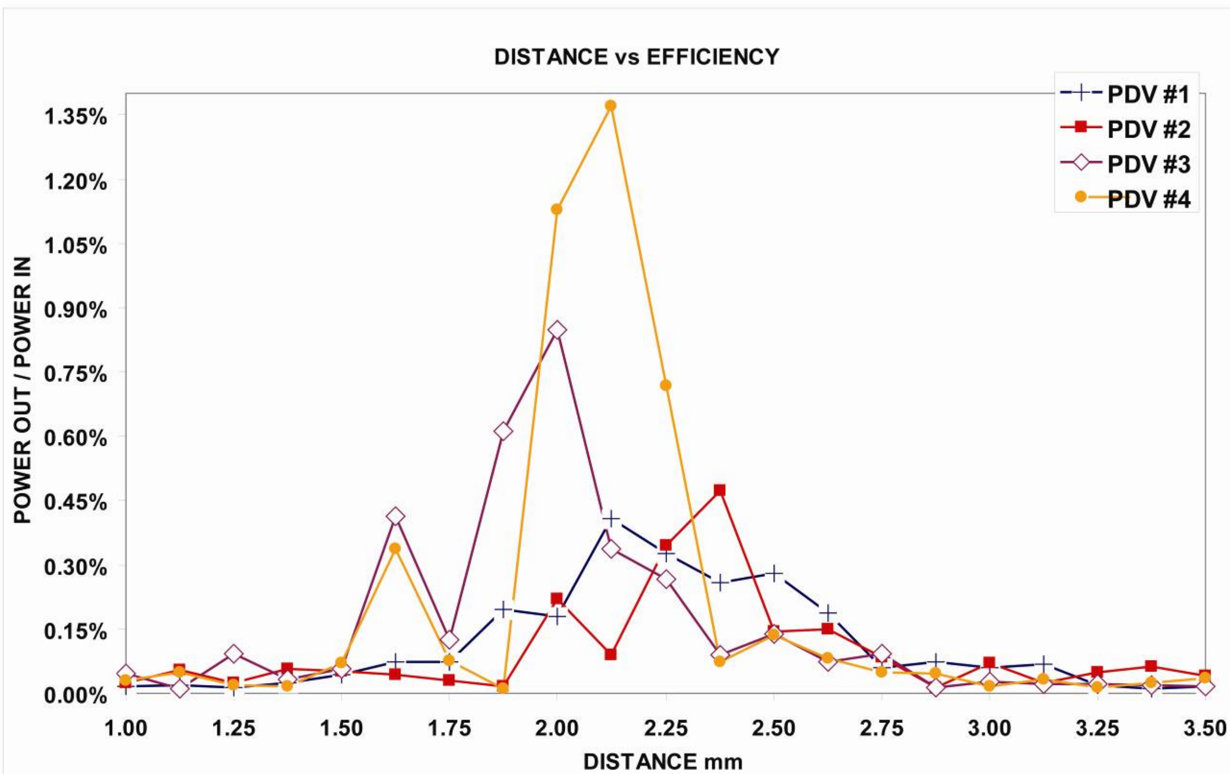


Fig. 10. VISAR and PDV light loss. The graphs seem to indicate that VISAR can be used over a longer tracking distance than PDV, but the opposite is true.

5. CALIBRATION, ALIGNMENT, AND ASSEMBLY

The assembly and calibration of the instrument canister involved a complex series of steps with tests at key points (Table 4). The transmission test is a baseline measurement to characterize light losses in the fiber as well as a qualitative check for cracks and roundness of light output. The back-reflection test checks the effects of unwanted return light due to bends in the fiber, dust, dirty connectors, bad coatings, and other factors. Both the transmission and back-reflection tests were performed many times during the assembly process.

Table 4. Calibration steps.

Test	**Description**
Transmission loss	Light throughput of fibers
Back-reflection	Return light with no target
Final position	Location of send and receive spots on a reticule
Z-axis test	Record efficiency at various Z locations by moving the simulated target

The optical system focuses at slightly different planes for VISAR and PDV due to chromatic aberration. This is permissible because each probe may be brought to best focus individually. The PDV diagnostic was aligned at 670 nm rather than 1550 nm, using reticules at the appropriate focal plane. The actual location of the conjugate points in the target plane is recorded during the final position test, as part of the calibration procedure.

The Z-axis test is a system check with a simulated target, fibers, mirror, and pellicle in place. The simulated target is translated along the Z axis with the power efficiency (output/input) logged in steps. Examples of data from this test are given in Figure 10. The Z axis is defined as being normal to the target surface and is also the direction of target travel during the dynamic test. The exact reflective characteristics of the real target are generally not known in advance.

The results would become unreliable if the simulated target has a smaller roughness length scale in the X–Y direction than the probe diameter or the typical laser speckle diameter. With the VISAR probes, Spectralon targets gave more believable results than bead-blasted aluminum targets, for example. With the PDV probes, the target needed to be partially specular or the return signal would be too weak to measure, so the partially diffuse side of an aluminum foil was used. An example of a Z plot that was generated for PDV probes is shown in the lower portion of Figure 10. The jagged structure in the PDV plot is due to slight nonuniformities in the target surface finish and the small size of the PDV fiber core (10 μm).

The PDV probe was able to track the target as it hit the pellicle in spite of the sharp fall-off in the signal strength of the shifted light that is simulated in Figure 10. This is due to the square root effect, as shown in Equation 1, and the fact that a Fourier transform can pull frequency data out of a noisy signal.

6. CONCLUSIONS

This series of experiments involved shocking a target with a high explosive, measuring the result with several optical diagnostic tools, and a downstream metallurgical examination. The diagnostic tools included radiography and velocimetry. Our team designed a combined PDV and VISAR velocimetry diagnostic that was successfully integrated into the larger effort. The combination of diagnostics that were employed complemented each other nicely. For example, understanding the metallurgical data depended to some extent on knowing the initial conditions during shock breakout and the level of damage prior to entering the foam catchment. A combination of VISAR and PDV velocimetry yielded complementary measurements that provided data in the first nanosecond of the experiment as well as for 15 mm of travel. (The target punctures a pellicle at 15 mm, so further data are not possible.)

The optical system for these experiments was quite simple, but the implementation was complex. The logistics of T&F for the many users (velocimetry, radiography, and detonation) required significant infrastructure.

The velocimetry diagnostic produced excellent data sets, so the calibration, alignment, and instrumentation designs were shown to be successful.

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10. Drilling technique provided by Sonic Mill, Albuquerque, New Mexico.
11. 3M 1640 Surface Saver Blue tape was used.
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Acknowledgments

This paper is dedicated to the memory of Michael Rutkowski.